DEVELOPMENT AND IMPLEMENTATION OF AN OPEN-BOX DISTRIBUTION-LEVEL PHASOR MEASUREMENT UNIT

BY

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THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Electrical and Computer Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2015

Urbana, Illinois

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ABSTRACT

Phasor measurement units (PMUs) are considered one of the most important measuring devices in power systems. PMUs are most commonly installed in substations, monitoring three-phase power. They provide synchronized measurements from any location where devices are installed. This synchronization is due to the micro-second Global Positioning System (GPS) time accuracy and is necessary for data to have meaning when compared across different locations. Among other purposes, data is used for post-mortem event analysis and system model validation.

This thesis aims to provide a deep understanding of the PMU's inner workings. Academia must know the inner workings of these devices in order to advance synchrophasor research and ensure standard compliance, as some devices do not fully comply with the existing IEEE (Institute of Electrical and Electronics Engineers) synchrophasor standards. Furthermore, it is difficult, if not impossible, to understand the causes of bad synchrophasor data since the software implementation of these devices is a mystery; although produced synchrophasors are all the same, as dictated by standards, the way these are calculated is undefined and varies depending on the PMU's manufacturer.

The chapters of this thesis explore the steps, challenges, and reasoning involved in the development of an open-box, distribution-level phasor measurement unit as well as the results obtained by deploying a network of these devices across the Urbana-Champaign distribution system.

ACKNOWLEDGMENTS

Many people helped bring this project to its final stages. It first started in my undergraduate studies when PhD student and retired Army Colonel Karl Reinhard looked for students to help with the synchrophasor data quality initiative sponsored by Prof. Peter W. Sauer. I would like to thank Andy Yoon and Kenta Kirihara for their contributions to the initial stages of the PMU development. Michael Quinlan was also part of the starting team and is the only student still working with me to bring this project to a finish, other than Karl Reinhard who still supervises our effort. Karl's vast knowledge and expertise taught me how to become a better leader and overcome obstacles of any nature, instilling in me a sense of confidence and responsibility.

I would like to also thank my adviser Prof. Peter W. Sauer for his support, freedom of research, and trust that we will bring this effort to an end. In addition, special thanks to Prof. Thomas J. Overbye for funding our research in order to obtain all the parts necessary for building the distribution-level PMUs. And finally, thanks to Jeremy Jones, a research programmer with the University of Illinois Information Trust Institute, for teaching me all the data networking concepts necessary and troubleshooting the problems we had in establishing an internet connection between the PMU and openPDC server.

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CHAPTER 1: INTRODUCTION

Phasor measurement units are devices most commonly found in substations and at various locations along the transmission system (110 kV and above). They can sometimes be incorporated into relays and other protective devices, therefore, on average, costing around $10,000. Still, according to Table 1, not all PMUs fully comply with existing IEEE standards [1]. Most of the devices pass the steady state voltage magnitude, phase angle, and frequency variation tests. However, many of them fail the dynamic tests (see Table 1). Furthermore, it is common for PMUs to transmit bad data due to various reasons.

A distribution-level PMU can help us understand the noncompliance and bad data causes, all while building a much cheaper device. The reason such a device has to be made from scratch is for us to understand exactly what can go wrong and to foster new ideas for distribution-level PMU research. New research is needed due to the Smart Grid initiative, as the distribution system promises to become more dynamic, requiring closer monitoring [2].

1.1 Understanding and Interpreting Synchrophasors

Power grid voltages and currents are approximated by sinusoidal waves. This is an approximation because the capacitive and inductive loads introduce harmonics that distort the wave. Phasors are the best way to mathematically express sinusoidal waves, and are, therefore, used to describe power grid behavior. A phasor X is defined as the magnitude and angle of a sinusoidal function $x(t)$, as below:

$$x(t) = X_m \cos(\omega t + \phi) \tag{1.1}$$

$$X = \left(X_m/\sqrt{2}\right)e^{j\phi} \tag{1.2}$$

The phasor representation is defined for the angular frequency ω, and so the frequency must be the same when comparing phasors in order to obtain meaning. When describing power grid behavior, this angular frequency is $2\pi 60$ rad/s for a 60 Hz system. A change from this nominal frequency will cause a change in phase; consequently, phasor calculation includes frequency oscillations so that phasors have meaning when compared across various locations. In particular, the phase angle will decrease if the frequency is less than nominal, and increase if higher than nominal, as shown in Figure 1.

To understand the power of synchrophasors, I will briefly describe the meaning of each calculated parameter when compared across multiple locations.

Power grid values, such as voltage magnitudes, angles, and complex power are governed by what is most commonly known as power-flow equations. These obey Kirchhoff's circuit laws and define the relationship between each parameter. In particular, real power flow is highly dependent on voltage angle differences (e.g. phase difference) and reactive power flow is mostly a function of voltage magnitude differences. The distribution voltages should remain within 5% of 120 VRMS (Voltage Root Mean Square). Therefore, reactive power must be locally injected in different locations to support a relatively flat voltage profile, as no large voltage variations are allowed in the distribution system. Lastly, a frequency higher than nominal indicates more power is being generated than necessary to serve all the loads; on the other hand, frequency lower than nominal indicates more power being used in loads than generated. It is not unusual to see frequency deviations of up to 40 mHz. Abnormal deviations in any of these parameters, however, can lead to grid instabilities which may cause loss of power and, ultimately, money.

In order for compared synchrophasors to have meaning, they must have been taken at the same time in all the locations, hence the prefix 'synchro-'. The synchronization is obtained by using the global positioning system technology. It provides a 5 V pulse at the beginning of each second, along with the correct time, accurate to within 1 μs. This GPS data is used for time-stamping synchrophasors.

1.2 Overview

The rest of this thesis is divided into various chapters, each discussing a different aspect regarding the building and deployment results of the distribution-level PMU. Chapter 2 is a survey of literature, describing similar efforts conducted by other schools or research groups. It concludes with a motivation behind our work and where our effort falls in the context of overall PMU research. Chapter 3 provides the PMU's design, functionality, and specifications. It also discusses problems, along with solutions that had to be implemented for producing a successful prototype. Chapter 4 shows the results obtained from a functioning PMU prototype. Chapter 5 provides a conclusion, along with limitations and suggestions for future work.

1.3 Figure

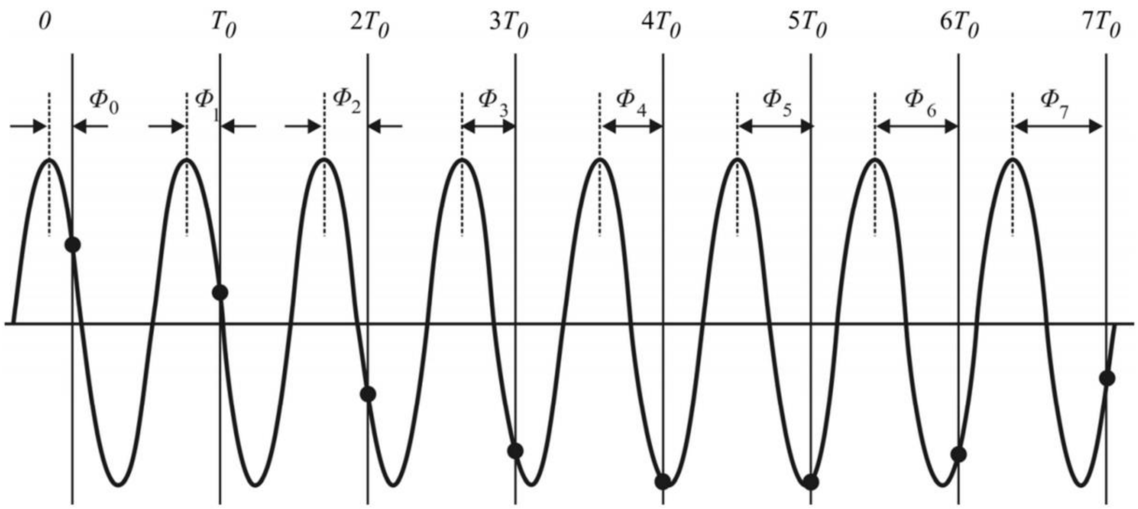

Figure 1: Sinusoidal wave with frequency greater than fundamental - the phase angle ϕ increases at each observed time T_0 seconds apart [3]

1.4 Table

Table 1: Conformance testing performed by Texas A&M University and XpertPower Associates in 2012 found that PMUs being marketed in the U.S. did not completely meet IEEE Std. C37.118.1-2011 specifications [1]

CONFORMANCE TEST RESULT SUMMARY

PMU	Class	Steady State Test									Dynamic State Test								
		Magnitude Variation			Phase Angle Variation			Frequency Variation			Measurement Bandwidth			Frequency Ramp			Step Change		
		TVE	FE	RFE	TVE	FE	RFE	TVE	FE	RFE	TVE	FE	RFE	TVE	FE	RFE	RT	DT	MO
PMU A	P	S	S	S	S	S	S	S	S	S	S	**F**	S	S	**F**	**F**	**F**	**F**	**F**
	M	S	S	S	S	S	S	**F**	S	S	S	**F**	S	**F**	**F**	**F**	S	**F**	**F**
PMU A-1	P	S	S	S	S	S	S	S	S	S	S	**F**	S	S	**F**	**F**	**F**	S	**F**
	M	S	S	S	S	S	S	S	S	S	S	**F**	S	S	**F**	**F**	S	S	**F**
PMU B	P	S	S	S	S	S	S	S	S	S	S	**F**	S	S	**F**	**F**	S	**F**	S
	M	S	S	S	S	S	S	S	S	S	**F**	**F**	S	**F**	**F**	**F**	S	**F**	S
PMU C	P	S	S	S	S	S	S	S	S	S	S	**F**	S	S	**F**	**F**	S	S	S
	M	S	S	S	S	S	S	S	S	S	S	S	S	**F**	**F**	**F**	S	S	S
PMU D	P	S	S	S	S	S	S	S	S	S	S	**F**	S	S	**F**	**F**	**F**	**F**	**F**
	M	S	S	S	S	S	S	S	S	S	**F**	**F**	S	**F**	**F**	**F**	S	**F**	**F**
PMU E	P	S	S	S	S	S	S	S	S	S	S	**F**	S	S	**F**	**F**	**F**	S	**F**
	M	S	S	S	S	S	S	**F**	S	**F**	**F**	**F**	S	S	**F**	**F**	S	S	**F**
PMU F	P	S	S	S	S	S	S	**F**	S	S	S	**F**	S	**F**	**F**	**F**	S	S	S
	M	S	S	S	S	S	S	**F**	S	S	**F**	**F**	S	**F**	**F**	**F**	S	S	S
PMU G	P	S	S	S	S	S	S	S	S	S	S	**F**	S	S	**F**	**F**	**F**	S	**F**
	M	S	S	S	S	S	S	S	S	S	S	**F**	S	S	**F**	**F**	S	S	**F**
PMU H	P	S	**F**	S	S	**F**	S	S	**F**	S	S	S	S	S	**F**	**F**	S	S	S
	M	S	**F**	S	S	**F**	S	S	**F**	S	S	S	S	S	**F**	**F**	S	S	S

S: satisfied; F: failure; P: class P; M: class M; TVE: total vector error; FE: frequency error; RFE: rate of change of frequency error; RT: response time; DT: delay time; MO: maximum over/under shoot.

CHAPTER 2: LITERATURE REVIEW

2.1 Frequency Monitoring Network (FNET)

The objective of the frequency monitoring network (FNET) is to create a low cost, wide-area frequency monitoring device that has high dynamic accuracy and low installation cost [4]. The FNET is a system comprised of two main components. One is the frequency disturbance recorder (FDR), Figure 2, a device developed by Virginia Tech to measure the 120 V distribution level outlet voltage, frequency, and phase. The second component is the information management system (IMS), which collects and analyzes FDR data [4]. The FNET was developed by the University of Tennessee in the early 2000s. It has a 1440 sampling frequency and outputs 10 packets per second, with the algorithm having the ability to output 1440 outputs per second, if needed. The frequency measurements are accurate to within 0.5 mHz and phase measurements are accurate up to 0.02 degrees.

Currently, there is a network of FDR devices across the country, and world, collecting data. Some uses include system model validation, post-disturbance scenario reconstruction, islanding detection of bulk power systems, and other wide-area applications. Data also captured frequency behaviors during the 2011 East Coast earthquake and Southwest blackout. These can be viewed in detail on the public FNET website. The FDR devices are available free of cost if placed in specific locations across the country, which will allow the FNET to increase its grid visibility.

Our focus in building the distribution level PMU is not for wide-area applications, but rather for gaining visibility into the distribution system by having a network of devices closely monitoring a specific area. Such high level of penetration will enable accurate fault detection and better understanding of secondary distribution level (120 V) voltage behavior.

2.2 OpenPMU

The openPMU project is an effort aimed at establishing an open-source platform for building a distribution level phasor measurement unit. It was started after realizing that different research groups are working on such a device in parallel, without collaboration. The openPMU system was originally designed and developed at Queen's University Belfast (QUB), United Kingdom. The project began around 2010. Due to its open-source nature, the system may be assembled for approximately $1000 [5]. So far, it has been reproduced by Colorado State University and Royal Institute of Technology, Stockholm.

The openPMU system, Figure 3, is split into multiple parts. It uses a standard National Instruments Data Acquisition device (DAQ) to acquire distribution level voltage data at 128 samples per cycle. A peripheral interface controller (PIC) microprocessor runs an Embedded C program written by the authors to timestamp data using the GPS 1 Hz square wave indicating the beginning of each second. The data is then sent to a computer running National Instruments (NI) LabVIEW for analysis and manipulation [6].

Although the openPMU platform aims to provide a platform for synchrophasor research, we had to develop our own phasor measurement unit in order to deeply understand causes of bad data quality. It is possible for an open source code to have small bugs that, if overlooked, will cause bad synchrophasor data without the user realizing the source of error. Furthermore, our goal was to have a device that can operate on its own, without the use of computers for data processing.

2.3 ARPA-E Micro-Synchrophasor Project

The Department of Energy's (DOE's) Advanced Research Projects Agency – Energy (ARPA-E) funded a research team comprised of various national laboratories and schools to investigate how the new distribution-level synchrophasor technology can be used to understand distribution grid behavior. The project started in April of 2013 and lasts three years.

The project collaborators are California Institute for Energy and Environment (CIEE), Power Standards Lab, University of California Berkeley, and Lawrence Berkeley National Lab. Their developed product is called a micro-phasor measurement unit (µPMU), Figure 4, and can be connected to the primary (12 kV) or secondary (120 V) distribution network to monitor three phase or single phase voltages.

The µPMU was designed to take 512 samples per cycle, compared to 24 samples in traditional synchrophasors. Furthermore, it provides millidegree phase resolution, which is an order of magnitude greater than other synchrophasors. Such high resolution is a necessity when trying to understand distribution level voltage behavior, as the phase angle does not change much across short distances. The first µPMUs were installed about three kilometers apart and the difference in voltage phase angle between the two locations is about 0.25 degrees [7]. The price has not yet been revealed, other than having a very low cost due to it being piggy-backed on the PQube, which is an existing distribution instrument for monitoring energy consumption and power quality.

Our project is different due to its ability to function during periods of grid instability and is focused on providing researchers insight into causes of bad synchrophasor data. This comes as a result of our PMU having an open-box approach. Furthermore, we started the project in the summer of 2012, almost a year ahead of the µPMU project.

2.4 PMU Standards

Synchrophasor requirements are dictated by the IEEE C37.118.1-2011 standard for synchrophasor measurements for power systems and C37.118.2-2011 standard for synchrophasor data transfer for power systems. Together, they define synchrophasor parameters under all operating conditions. Furthermore, they define a method for real-time exchange of synchrophasors between power systems equipment, such as between PMUs and phasor data concentrators (PDCs). They do not, however, specify software, hardware, and methods for computing synchrophasors. This allows for the same result to be obtained using very different methods.

An updated and revised version of the standard was then released, known as C37.118.1a-2014. The 2011 version demanded a few standards that were not achievable with the available hardware. In particular, the new version revised Table 4 through Table 10 of the original 2011 standard, mostly dealing with dynamic conditions.

The IEEE synchrophasor standard C37.118.1-2011 presents a quantity called total vector error (TVE). TVE expresses the difference between the estimated synchrophasor and its theoretical value, expressed in per unit, defined in Equation 2.1:

$$TVE(n) = \sqrt{\frac{(\hat{X}_r(n)-X_r(n))^2+(\hat{X}_i(n)-X_i(n))^2}{(X_r(n))^2+(X_i(n))^2}} \tag{2.1}$$

$\hat{X}_r(n)$ and $\hat{X}_i(n)$ are the sequences of estimates, and $X_r(n)$ and $X_i(n)$ are the sequences of the theoretical values. TVE is allowed to have a maximum value of 1%. It has a visual representation in Figure 5. It is important to note that TVE only consists of voltage and phase errors; frequency is not part of the phasor definition, as explained in Section 1.1.

A phase error of 0.57 degrees will result in a TVE of 1% just by itself. An error of 0.57 degrees is equivalent to 26 μs and 31 μs for a 60 Hz and 50 Hz system, respectively. TVE of 1% further implies that the maximum voltage error allowed is 1%, given the phase is exact. Lastly, the maximum allowed frequency error is 0.005 Hz.

2.5 Figures

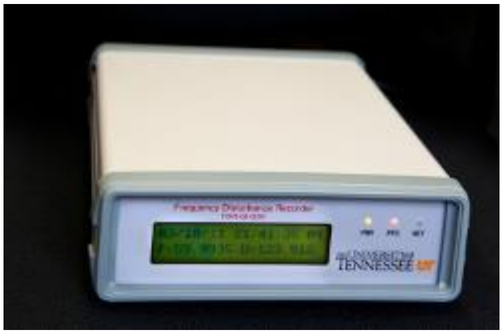

Figure 2: FDR component of the FNET [8]

Figure 3: Measurement device used in the openPMU platform [9]

Figure 4: ARPA-E µPMU prototype [7]

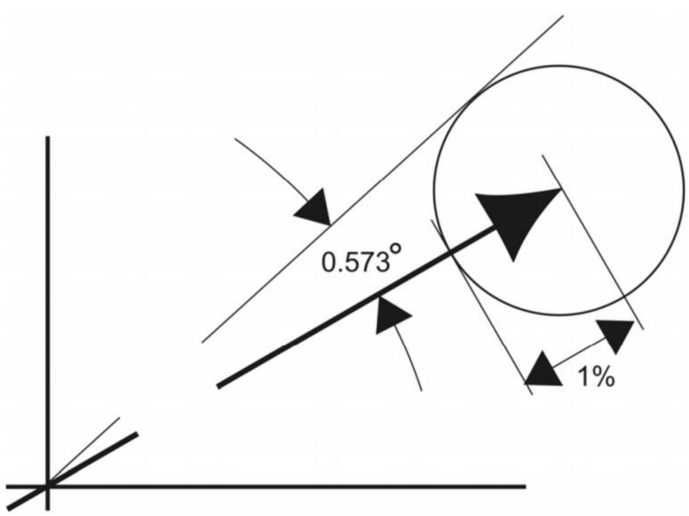

Figure 5: Illustration of 1% TVE [3]

CHAPTER 3: PHASOR MEASUREMENT UNIT DEVICE DESIGN

3.1 Design and Motivation

This project was started as part of the Synchrophasor Data Quality (SDQ) initiative at the University of Illinois at Urbana-Champaign under the supervision of Professor Peter Sauer and PhD candidate Karl Reinhard, in the summer of 2012. The aim was to build an open-box, secondary distribution level (120 V), low cost phasor measurement unit. As the distribution system becomes increasingly more dynamic due to the renewable and smart grid initiatives, it also requires closer monitoring. Transmission level PMUs alone cannot provide the visibility required for monitoring. Furthermore, a secondary distribution level PMU is cheaper to manufacture as it does not have to monitor three-phase voltages and high currents, only one-phase wall voltage. However, there are currently no standards in place that dictate the allowed distribution level synchrophasor errors produced by these devices, though researchers agree that these standards must be stricter. This is because distribution level PMUs are installed in locations that are not as far apart as those installed in the transmission system. Therefore, the measurements must have a higher resolution to accurately interpret synchrophasor data in a distribution context.

Synchrophasor data quality sources have many classifications, including data processing, digital signal processing, equipment specifications, installation, measurement, network failure, PMU configuration, and PMU standards. The hope was that a device built from scratch would give us an understanding of data quality issues caused by the hardware and software, covering most of the error sources.

Our distribution level PMU, Figure 6, has a sampling frequency of 10 kS/s and can be reprogrammed to higher frequency if the user so desires. It has a user selectable output rate of 10 Hz or 20 Hz. Section

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Some of the content presented in this chapter has been previously published in [10].

3.4.1 discusses how the hardware's clock will introduce synchrophasor errors if 30 Hz or 60 Hz reporting rates are allowed. An important feature is its battery backup that allows the device to operate during periods of grid instability up to one hour. The most interesting grid behavior happens during such periods and having that data available helps validate system models as well as understand causes of grid instabilities. Lastly, the parts needed to reproduce our device cost only $350.

3.2 Hardware

The block diagram of our device is shown in Figure 7. It uses a National Instruments myRIO-1900 as the main piece of hardware. It has a Xilinx Z-7010 field-programmable gate array (FPGA). Such a processor is desired because it provides accurate software loop timing needed to collect, process, analyze and report the synchrophasor data. It also receives the GPS second pulse and Coordinated Universal Time (UTC) used for synchronization and time stamping data. The wall voltage must be stepped down in order to allow the ± 10 V analog inputs to sample it. This is done through a 24:1 resistor divider circuit. We chose a resistor divider rather than a transformer in order to optimize the cost and size of our PMU. The ±10 V analog input has an absolute accuracy of ±200 mV, according to the data sheet, which corresponds to a 2% maximum voltage error; this topic will further be explored in Section 3.4.1.

An AC/DC converter powers the device and also keeps a 12 V battery charged to provide backup power during periods of grid fluctuations. An LCD (liquid-crystal display) updated every second displays the latest synchrophasor to the user. There are two options for storing synchrophasors. This can be done locally on a flash drive, or sent to an openPDC server via C37.118.2 communication standard for remote storage. A phasor data concentrator is a server that aggregates synchrophasors from multiple locations, allowing data archival over long periods of time. The openPDC is just an open source phasor data concentrator that complies with the synchrophasor communication standards.

3.3 Software Operation

In order to understand the difficulties encountered trying to produce an accurate synchrophasor, one must understand the software side of it. We use NI's LabVIEW software to program the myRIO-1900. LabVIEW is a visual programming language widely used across industry and academia. The reason we chose NI hardware and software is because, although pricier than other alternatives, they provide excellent products and customer support. Furthermore, they have strong connections with the university and were able to offer hands-on training.

Software on the myRIO samples the wall voltage (120 V) at 10 kS/s. In order to produce 10 phasors per second, each second data must be divided into 10 fragments, or synchrophasors. Each fragment, therefore, consists of 1000 points. The voltage RMS, frequency, phase, and timestamp are then calculated for each fragment, as discussed in the paragraphs below. The reason why we wait for a whole second worth of data before calculating synchrophasor parameters is because the myRIO's 40 MHz clock is only accurate to within 1 µs; over time, this adds up and translates to either having an extra sample point or losing a sample point. The extra sample point will interfere with the synchrophasor calculation if not accounted for. In order to account for the lacking, or extra, point in our samples, we calculate exactly how many sample points have been taken during the last second. This, of course, introduces a one second latency between the time when data has been taken and the synchrophasor generated has been sent to the user.

According to the IEEE C37.118 synchrophasor standard, phase is defined as the deviation in degrees from a standard cosine wave. In LabVIEW, phase is calculated using the Extract Single Tone Information VI. LabVIEW Virtual Instruments (VIs) are prebuilt programs that are available for users to simplify their work. Frequency is also calculated using the same prebuilt VI. The VI has the time signal (1000 data points worth of data) as the input, along with several other optional inputs. Detected frequency and phase in degrees are among the several outputs. The VI calculates these parameters by extracting the wave's fundamental frequency through complex mathematical derivations.

Voltage RMS is also calculated using a prebuilt RMS VI. It does so by using the standard RMS formula, Equation 3.1, where V_i stands for the voltage value of the i^{th}sample.

$$V_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} V_i^2} \tag{3.1}$$

3.4 Hardware's Clock Limitations

3.4.1 Appropriate Reporting Rates

Section 3.1 mentioned that we implemented a user selectable output rate of 10 Hz and 20 Hz for our device. The reason for not having 30 Hz or 60 Hz as output rates has to do with the hardware's clock frequency. Anything divisible by 60 is also divisible by 30; therefore, I will only discuss the reason not having a 60 Hz output rate as an option. Thus, by inference, the same reason applies to not having a 30 Hz output rate.

To begin with, 10 kS/s does not evenly divide by 60; therefore, a different sampling frequency must be chosen for a 60 Hz output rate. Choose instead 5940 samples per second, which corresponds to 99 samples per synchrophasor. We use the hardware's clock to time the amount of clock ticks until the next sample will be taken. The number of clock ticks must be an exact number, as the software, by definition, cannot start an operation during fractions of clock ticks. A sampling rate of 5940 translates to a voltage sample being taken every 6734.007 clock ticks. The software will interpret this as 6734 ticks, thereby introducing a timing error of 0.168 ns in each data point. This error grows over time and could be eliminated if hardware with a different clock is chosen instead. Also, this error is present before even beginning to calculate synchrophasor parameters, which is why it should be completely avoided. In order to eliminate this error for a 60 Hz reporting rate, the clock's frequency must be exactly divisible by the sampling frequency, while the sampling frequency must be divisible by 60. This is never the case with a 40 MHz clock, as is present in the NI's myRIO-1900. A sampling frequency of 5940 S/s is the one with the least amount of timing error, though. This timing error is the reason the 30 Hz and 60 Hz report rates are not available for the user to select. Instead, 10 Hz and 20 Hz work fine, not having any timing issues caused by the clock frequency. We are working on deriving a 30 MHz clock from the 40 MHz clock provided, which will allow report rates of 30 Hz and 60 Hz.

In order to estimate the accuracy of synchrophasor parameters, all sources of error must be taken into account. Clock frequency is a source of error that can be remedied. We wrote a program to calculate the amount of clock ticks between rising edges of GPS pulses. We observed a maximum error of 40 ticks in the 40 MHz clock. This error corresponds to a timing error of 1 µs each second. Its effect on synchrophasor's frequency, rms, phase, and time-stamp calculations are presented in the subsections below.

3.4.2 Clock Error's Impact on Frequency Calculation

A 1 µs/s timing error introduces a 60 µHz error in frequency calculation. This is due to 60 cycles taking place in 1 second ± 1 µs. The error does not depend on the output rate. More importantly, it does not propagate from second to second because the only timing error that matters is the relative error between the beginning and end of the synchrophasor, which always stays at a maximum of 1 µs. The synchrophasor standards allow a 5 mHz frequency error. Furthermore, this is within the allowed 5 mHz frequency error, assuming all the other parameters do not have any error. This, of course, is not the case, but the frequency error is well within the allowed range.

3.4.3 Clock Error's Impact on RMS Calculation

Voltage root mean square calculation only depends on data values, as per Eq. 3.1, as long as the points are evenly spaced. Assuming the hardware's clock remains relatively constant during each synchrophasor, only changing over long periods of time, the clock error does not affect voltage root mean square calculation.

3.4.4 Clock Error's Impact on Phase Calculation

Phase plays a very important role among the calculated synchrophasor parameters. Some argue it should be accurate to millidegree values, as distribution phase does not change as much as transmission level voltage phase. Therefore, any errors affecting phase must be taken into account and eliminated as much as possible.

The synchrophasor standard allows a maximum phase error of 0.572 degrees. This corresponds to a time error of 26 μs for a 60 Hz system and a 31 μs for a 50 Hz system [3]. The hardware's clock having an error of 1 μs will allow the PMU to operate for 26 seconds before reaching the allowed limit. Section 3.3 described the clock error being taken into account by calculating the exact number of voltage sample points taken during the previous second. This stops the phase error from propagating to the next second, thereby limiting it to 1 μs, corresponding to 0.022 degrees in a 60 Hz system.

3.4.5 Clock Error's Impact on Time-Stamp

Time-stamp is defined as the time in the middle of the synchrophasor. Time-stamp error caused by the hardware's clock error is dependent on the output rate and will increase from synchrophasor to synchrophasor if code was not written as described in section 3.3.

Figure 8 shows one second worth of voltage data (10,000 samples, 10 Hz output rate). It illustrates the fact that the last data point in the second is off by 1 μs. This comes from the hardware's clock being off by a maximum of 1 μs. In this case, this will translate to a time-stamp error of 0.05 μs for the first synchrophasor in the second, and will add up to the last synchrophasor having a time-stamp error of 0.95 μs. This is in addition to the 1 μs timing error inherent to the GPS system. Therefore, a 10 Hz output rate will have a time-stamp error of 1.95 μs. Allowed time-stamp error is not specified in the standards because time-stamp error will directly translate to an error in phase, because phase is the only parameter that has a strong dependence on time. Frequency and voltage calculation will be affected much less if the synchrophasor starts a couple of data points later. However, phase will be different.

3.4.6 Total Vector Error Caused by Hardware's Clock

Recall that Eq. 2.1 presents the definition of total vector error, which, according to the synchrophasor standards, is allowed to reach a maximum of 1%. It is important to note that this error is only a combination of voltage magnitude and phase errors. It does not take into account frequency error. Knowing the theoretical accuracy of each synchrophasor parameter (voltage, phase) allows us now to understand where the error falls within the TVE criterion. The myRIO's data sheet specifies a ±200 mV absolute accuracy for its analog inputs (±10 V), which is where the voltage is measured. This error is outside of the 1% TVE limit. However, absolute accuracy is a function of input voltage, offset, system noise, and temperature drift. If several of these parameters are in control then the readings may increase in accuracy, up to a minimum voltage error of ±0.005 V for its ±10 V inputs. This corresponds to a 0.05 % voltage error. Therefore the voltage error can be anywhere between 0.05% and 2%, with the error most likely being closer to the lower bound since some parameters affecting absolute accuracy are assumed to be in control, such as temperature.

Theoretically, phase calculation error is limited to 1 µs, corresponding to 0.022 degrees for a 60 Hz system and 0.019 degrees for a 50 Hz system. Figure 9 shows the TVE as a function of phase angle error for various voltage errors. Assuming a 0.022 degree error in phase, voltage is then allowed to have an error of approximately 0.99%. Still, we do not know the actual voltage error unless we have the PMU tested for synchrophasor standard compliance; then we would be able to tell if our device, theoretically, complies with the 1% TVE standard.

3.5 Location Placement

Location placement plays a very important role in the deployment process of distribution level phasor measurement units. There have been many graph theory approaches to placement of PMUs within the transmission system. However, these do not necessarily apply to the distribution system. These transmission level placement algorithms heavily rely on the meaning of synchrophasors obtained from the transmission system. Synchrophasor, in particular phase interpretation, might have a different meaning within the distribution system. For example, there could be phase shifting transformers and capacitor banks between different distribution level PMUs that will affect phase measurements. If these intermediate devices are not taken into account, it becomes impossible to give meaning to voltage phase. Even if the distribution layout between PMUs is known, it might still be very difficult to give meaning to voltage phase. Another aspect applying to location placement is the three-phase nature of the distribution system. Compared synchrophasors must be taken from the same phase, as any phase imbalance affects voltage magnitude and voltage phase interpretation.

The field of PMU location placement within the distribution grid is in need of great research to understand impediments that can affect measurement interpretation along with a way to obtain grid visibility while minimizing the number of deployed devices. Moreover, synchrophasor interpretation might differ in a distribution system compared to transmission synchrophasors. This, too, has to be further researched.

3.6 Figures

Figure 6: Distribution level PMU prototype

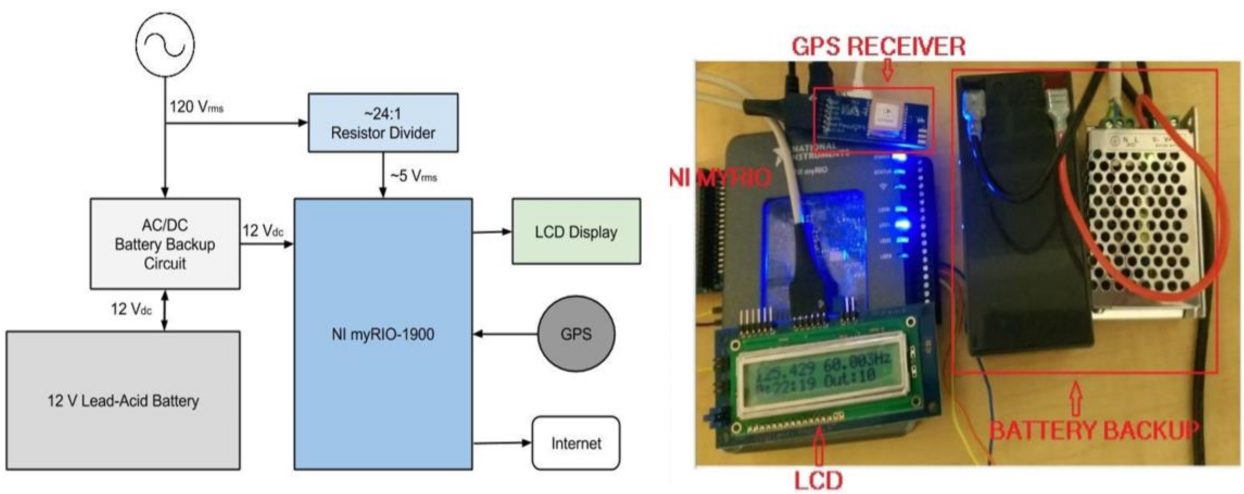

Figure 7: PMU Block diagram (left), PMU components (right)

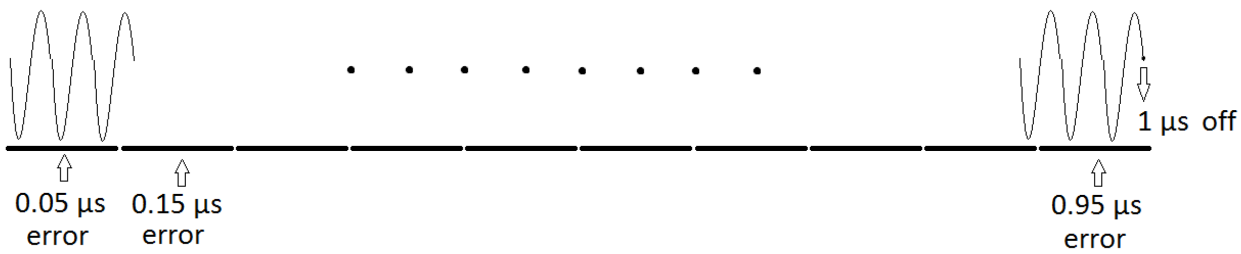

Figure 8: One second worth of data being affected by the hardware's clock error

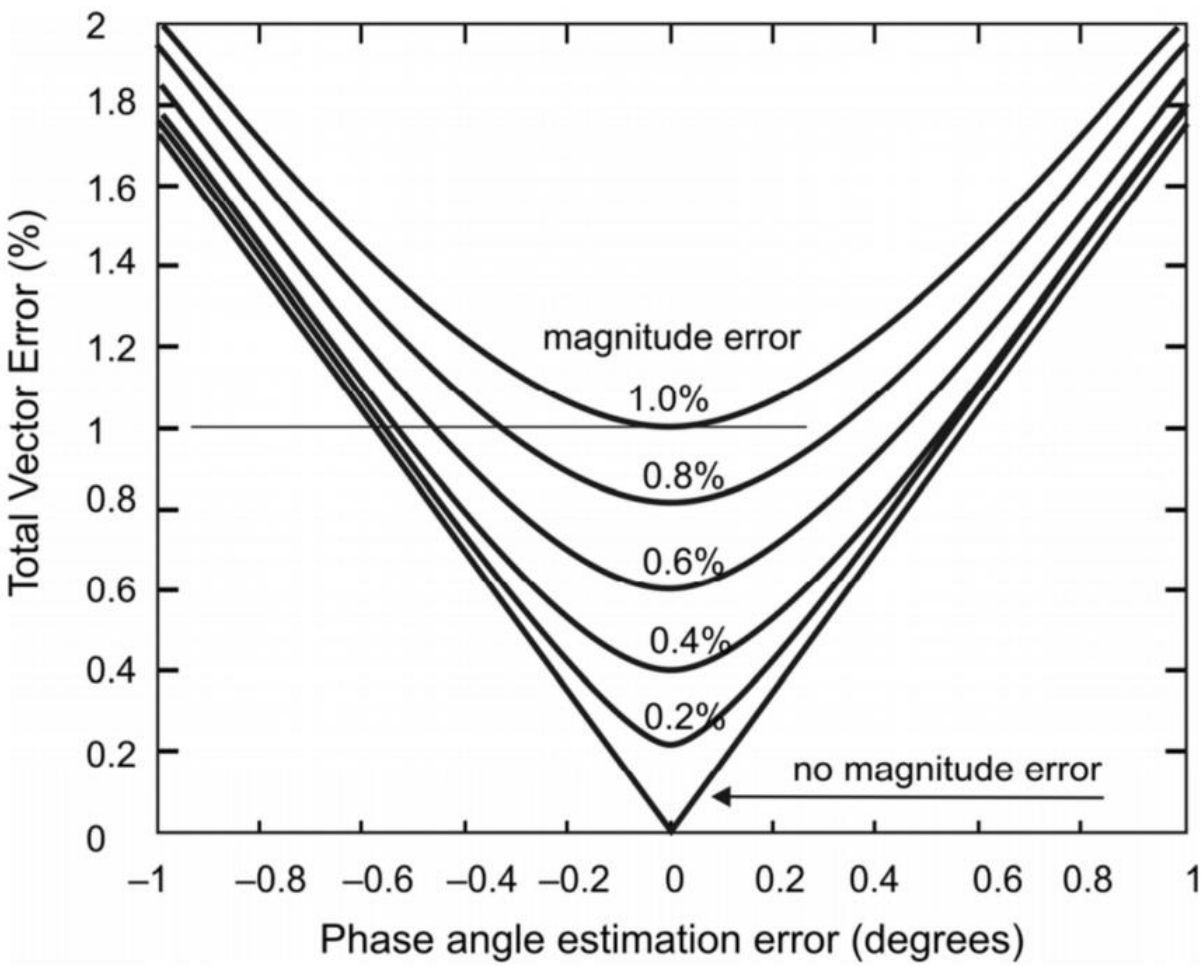

Figure 9: TVE as a function of phase for various magnitude errors [3]

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Sample Hour-Long Synchrophasor Data

Figure 10 through 13 show a sample hour's worth of synchrophasor data consisting of voltage frequency, voltage magnitude, and voltage phase, respectively. This data is reported at 10 Hz; therefore, each graph consists of 36000 points. Among the observed data, frequency tends to remain within 40 mHz of nominal frequency. Voltage RMS behaves more erratically, sometimes with values outside of the allowed 5% deviation from 120 V. The most common events are quick voltage dips, as seen in Figure 11. Zoomed in figures of these dips are shown in Figure 19 and Figure 20. These seem to have the same regeneration behavior, with each dip approximately 0.6 V and lasting for approximately one second. Other noticeable events are steps or drops in voltage, representing transformers changing their tap ratios to ensure distribution level voltage regulation. Voltage phase behavior, however, does not yet provide much meaning on its own.

4.2 Comparison of Synchrophasors Obtained by Different Output Rates

Figure 13 through 19 show comparison of synchrophasors obtained using different output rates. In particular, Figure 13 shows synchrophasors obtained by 10 Hz output rates from two devices installed at the same location. Figure 14 shows the same devices, but one running at 10 Hz while the other at 20 Hz output rate. Finally, Figure 18 shows both devices running at 20 Hz output rate.

Since both devices are plugged in the same location, therefore sampling the same voltage, the synchrophasors obtained must match. Frequencies, indeed, match across the two devices regardless of output rate chosen. There is a small difference in voltage values, seen in Figure 18, due to my altering the voltage scaling factor for easier visibility; the voltages also match. Their behavior is very important, and the fact that an event is captured by both devices is critical because it enables proper event detection across multiple PMUs.

Voltage phase, however, does not match across the two devices; phase is the synchrophasor parameter that requires the most accuracy and its exact calculation is critical to understanding its applications. When it comes to voltage RMS, its overall behavior is a good indicator of unusual events; phase, on the other hand, requires much more than just obtaining its overall behavior. It requires, as some suggest, that we know phase values to millidegree resolutions. Our device is yet not capable of obtaining such results. Suspected reasons are discussed in Section 4.5.

4.3 Unusual Event Detection

The major benefit of a distribution level PMU is its ability to reliably capture unusual events. Such an event was captured and its impact can be seen in voltage frequency, root mean square, and phase, as shown in Figure 21 through 24. At the beginning of the event, frequency dropped by 300 mHz and lasted for a tenth of a second, after which it recovered to its previous vales. Voltage value dropped by 5 VRMS and recovered over the course of one minute, in multiple steps, as seen in Figure 22. It is more difficult to see the event's impact on voltage phase, unless one knows where to look. The data containing the unusual event was taken overnight in Everitt Laboratory on the University of Illinois campus. I may only speculate about the cause of the event, as it is outside the scope of this research.

4.4 Figures

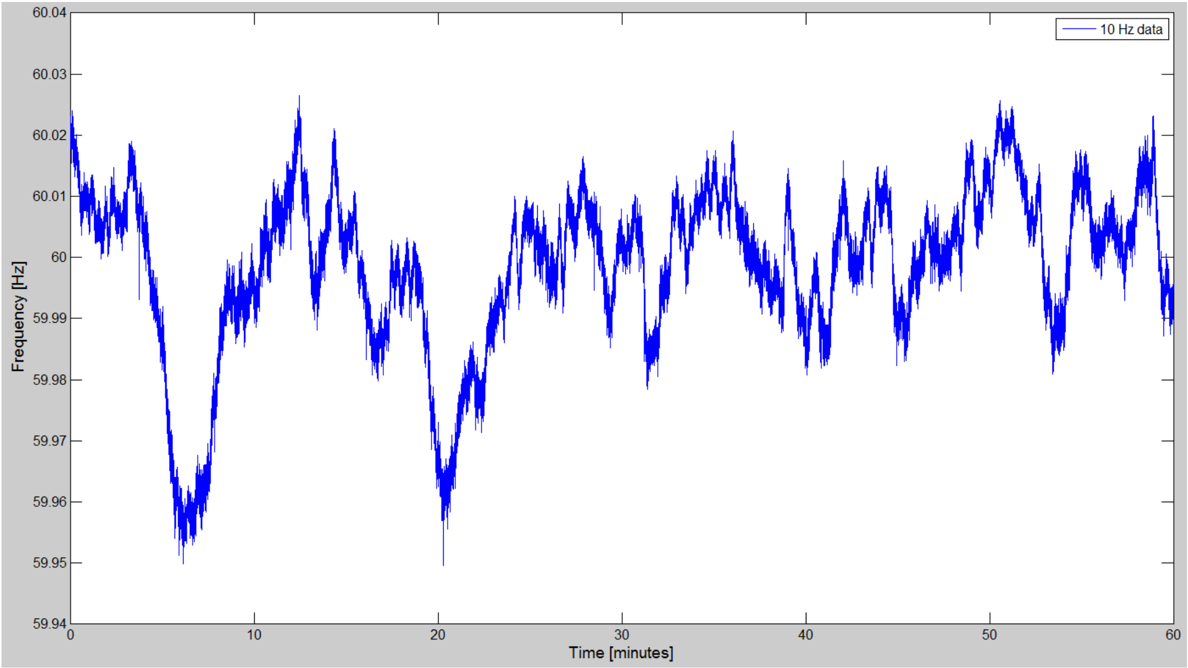

Figure 10: Voltage frequency data sample

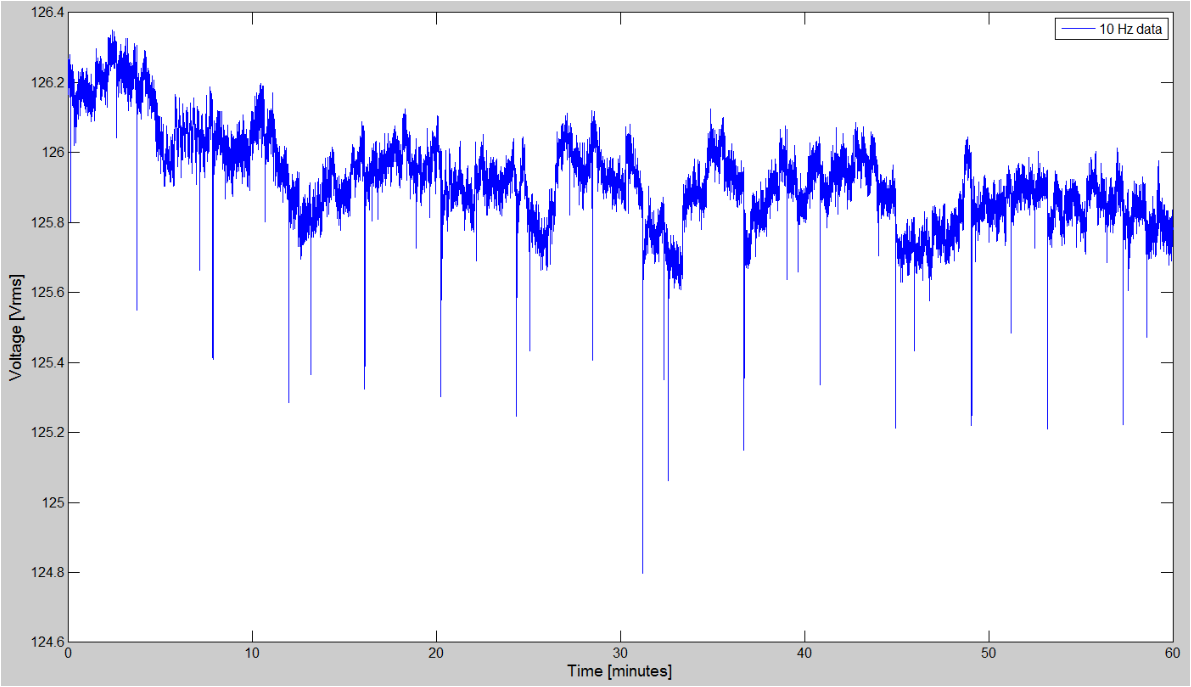

Figure 11: Voltage RMS data sample

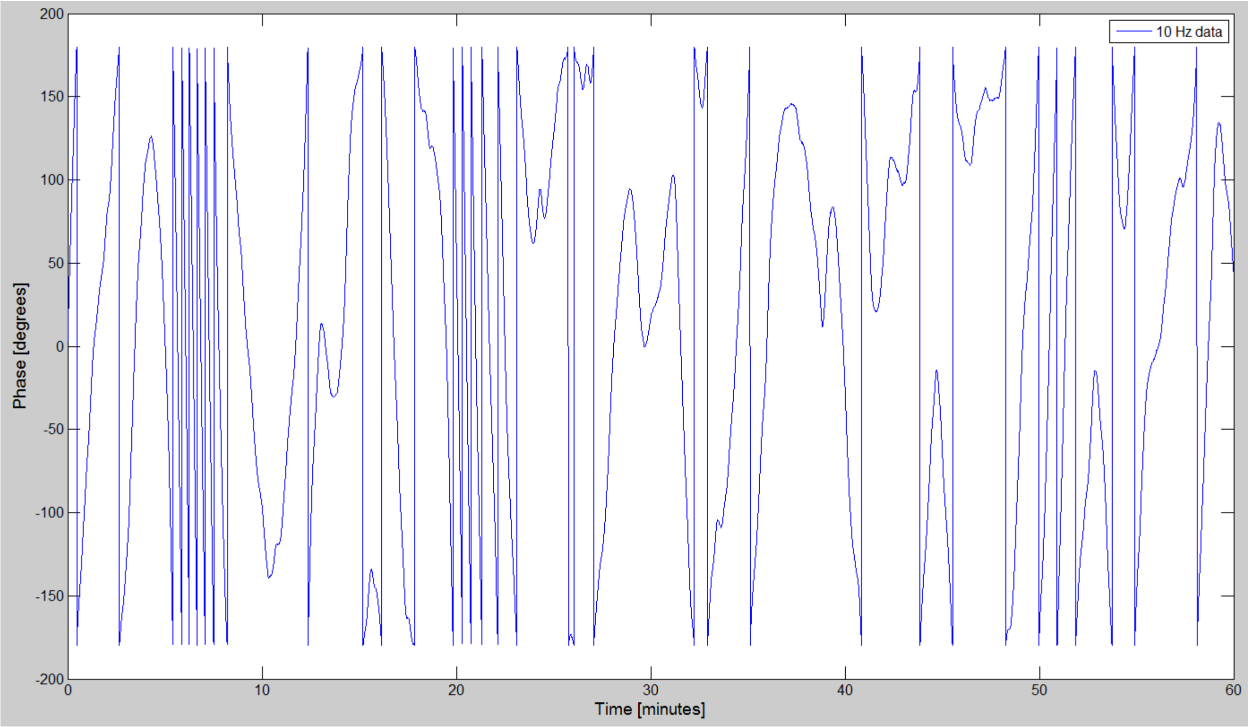

Figure 12: Voltage phase data sample

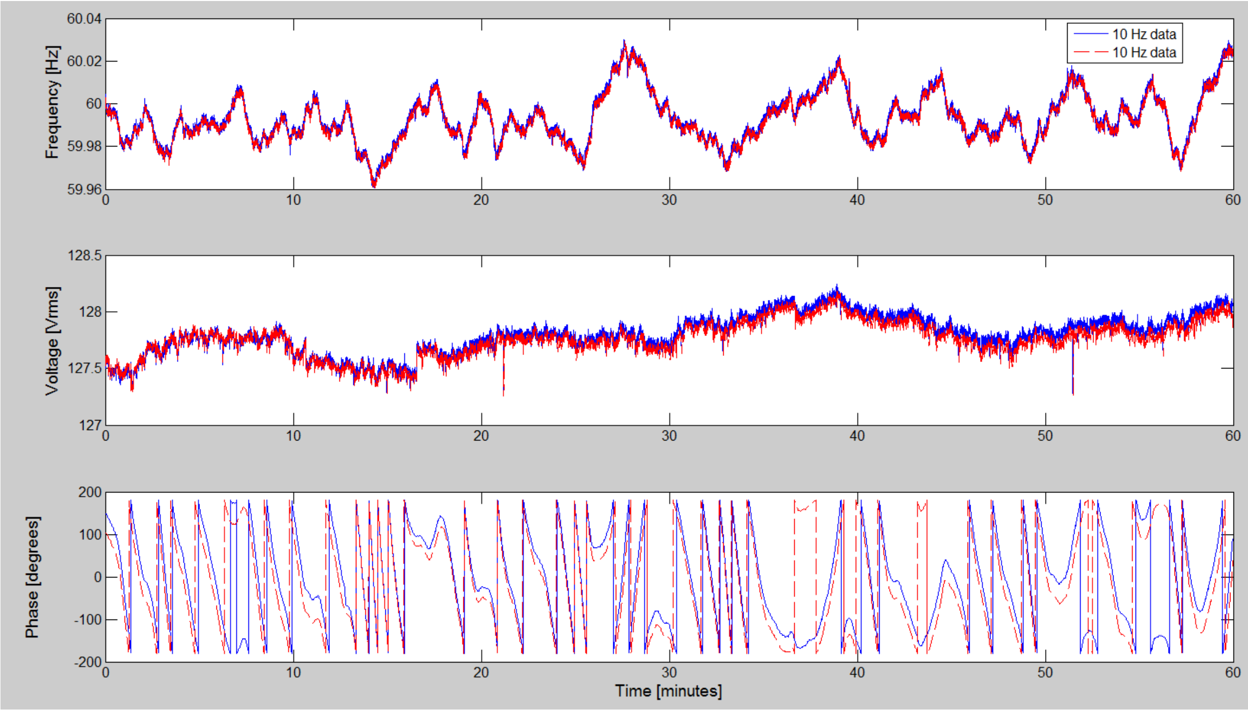

Figure 13: Comparison of 10 Hz vs. 10 Hz synchrophasors collected at the same location

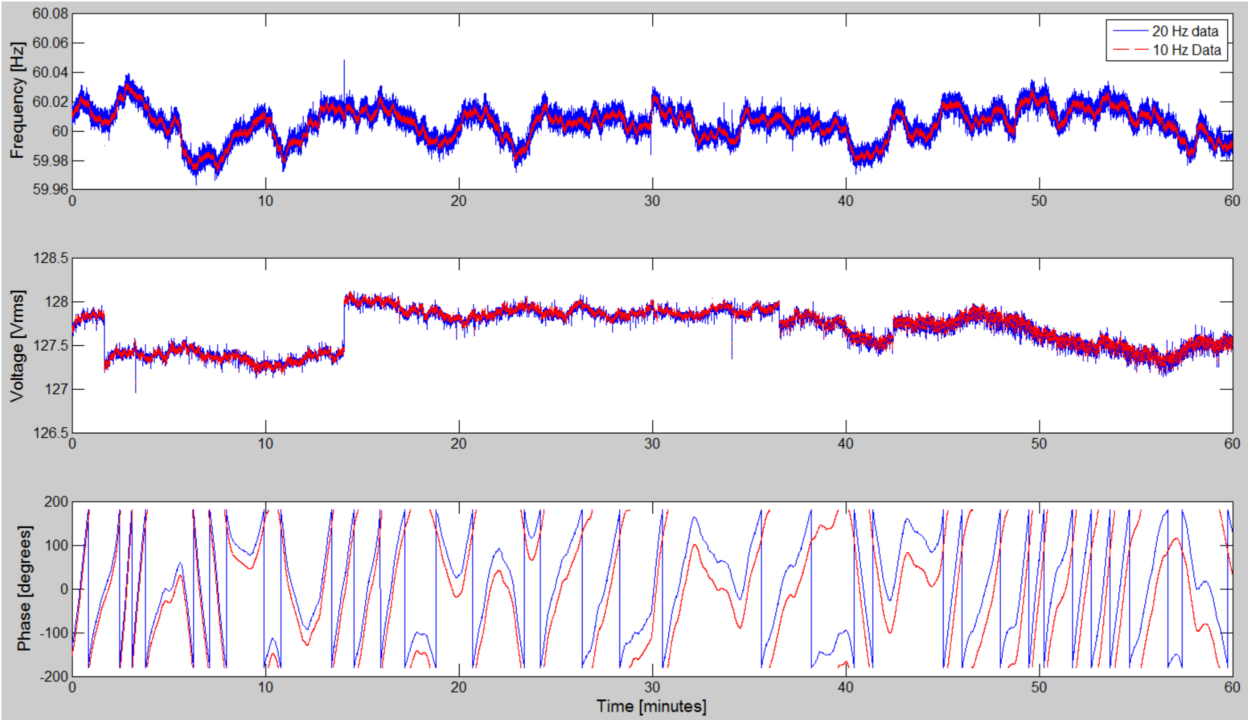

Figure 14: Comparison of 10 Hz vs. 20 Hz synchrophasors collected at the same location

Figure 15: Minute long frequency sample at different reporting rates

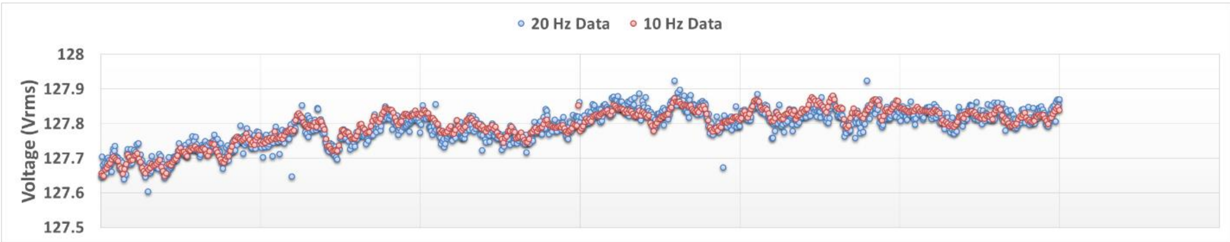

Figure 16: Minute long voltage sample at different reporting rates

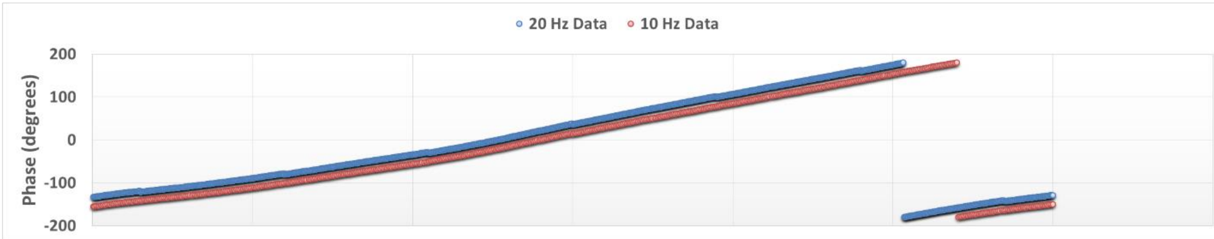

Figure 17: Minute long phase sample at different reporting rates

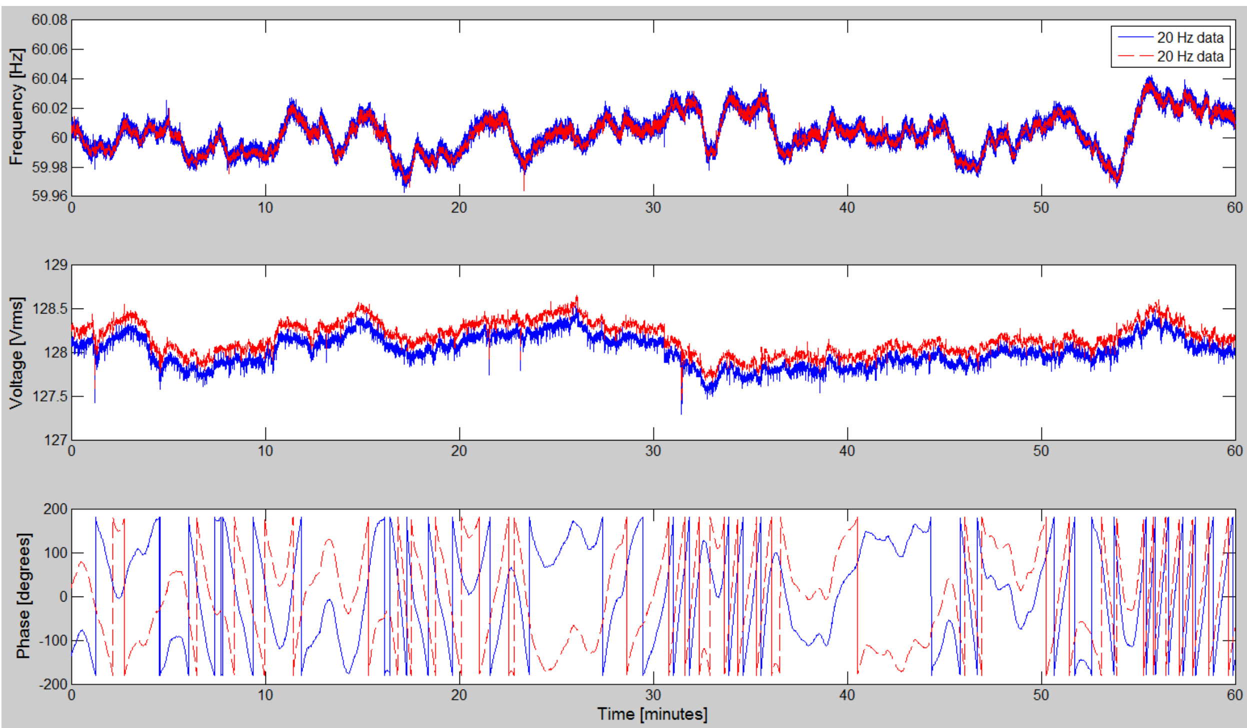

Figure 18: Comparison of 20 Hz vs. 20 Hz synchrophasors collected at the same location

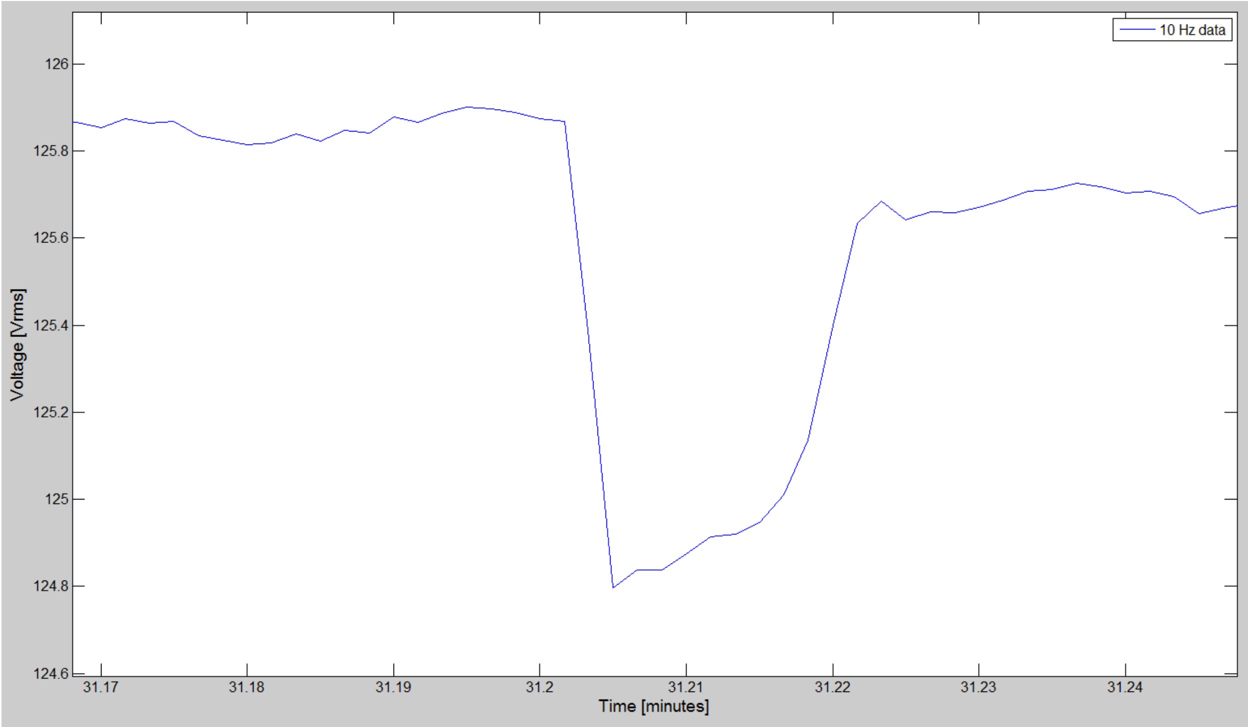

Figure 19: Voltage dip

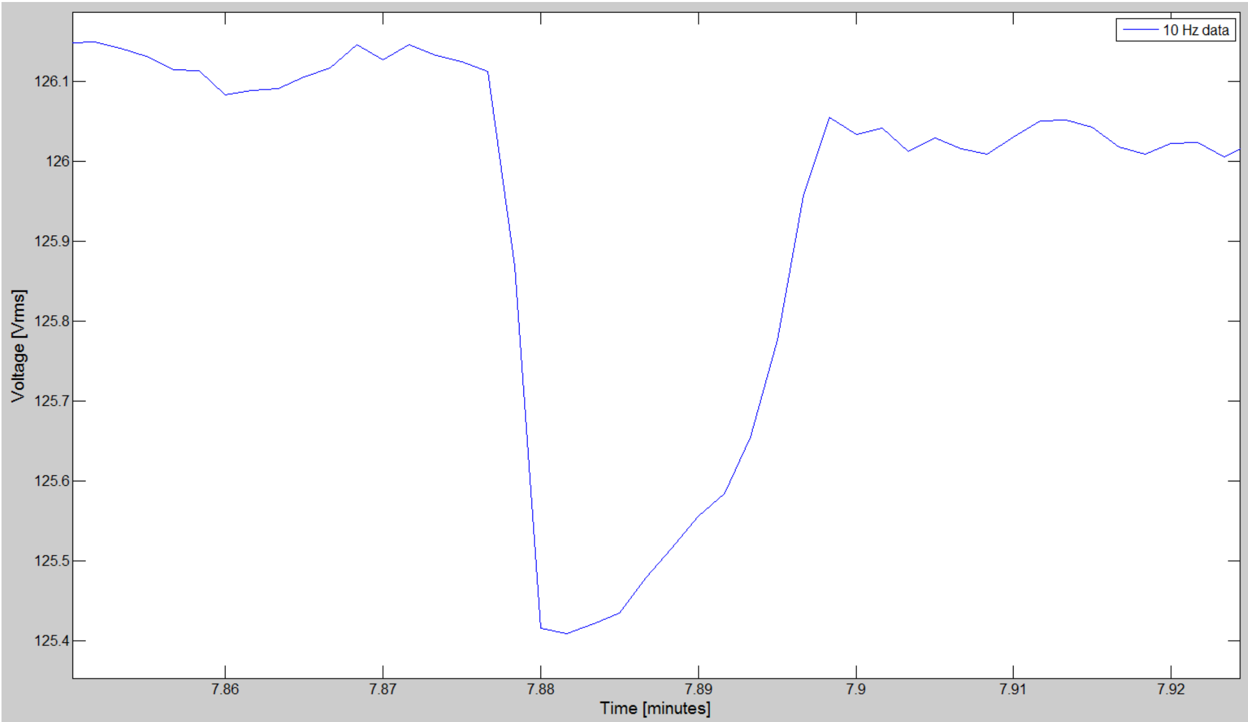

Figure 20: Reoccurring voltage dip

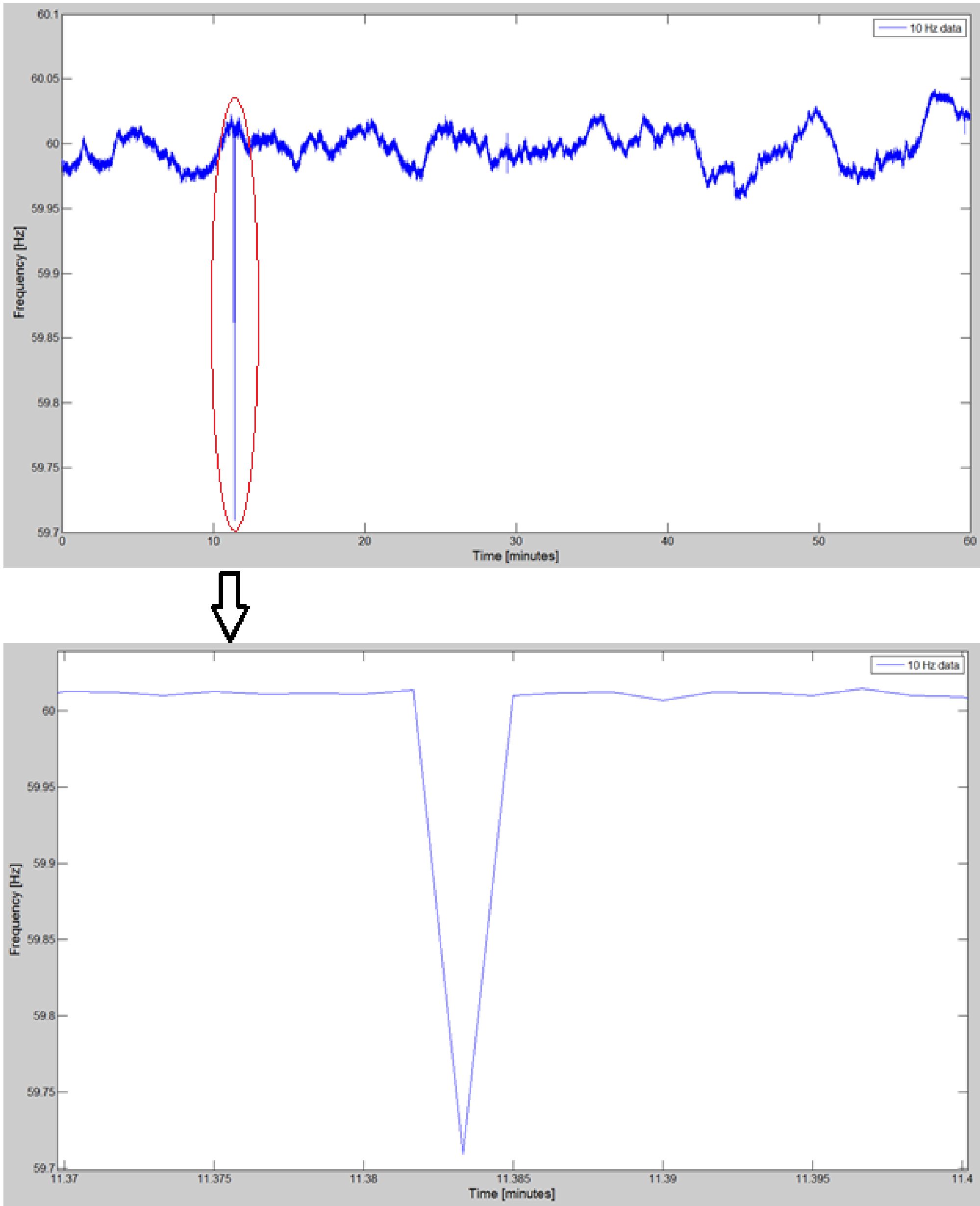

Figure 21: Unusual event introduces dip in frequency (top); zoom in on frequency dip (bottom)

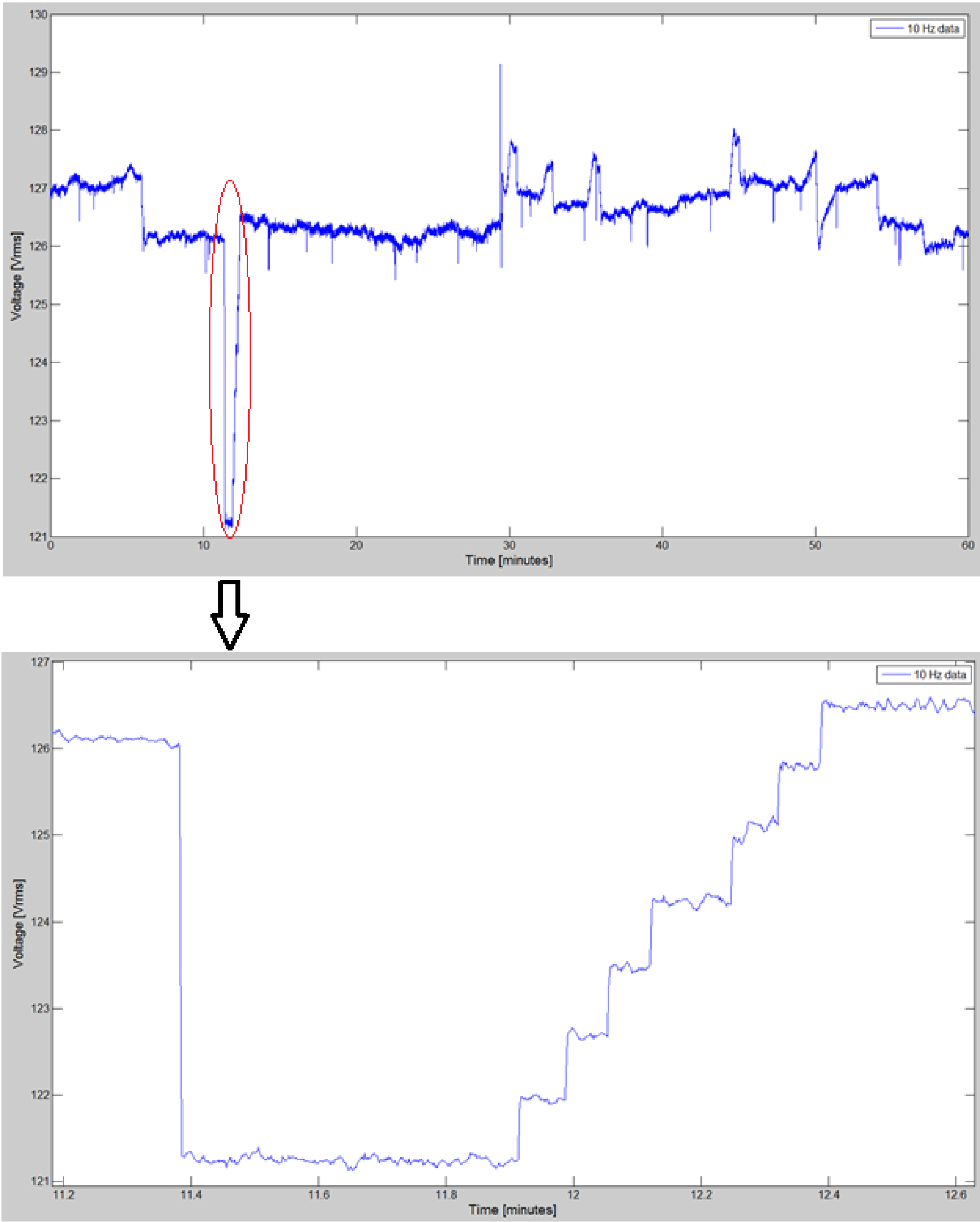

Figure 22: Unusual event's impact on voltage (top); zoom in on voltage drop (bottom)

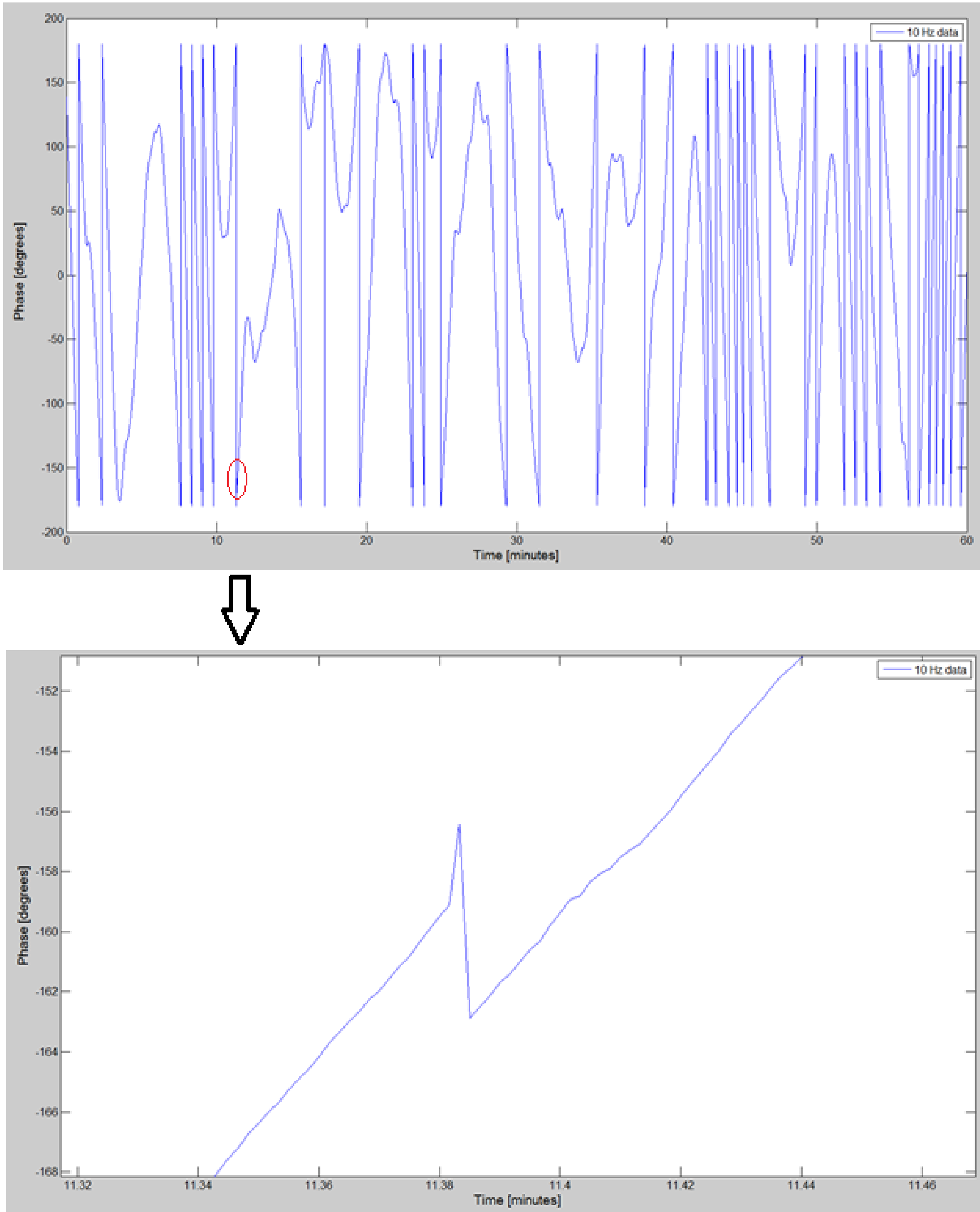

Figure 23: Voltage phase during the hour unusual event happened (top); zoom in on phase at the beginning of event occurrence (bottom)

CHAPTER 5: CONCLUSION

Phasor measurement units are considered to be one of the most important measuring devices in the future of power systems. This is due to the Smart Grid initiative and the rise of renewable energy and electric vehicle integration. As a result, the distribution system becomes more dynamic, and therefore, a distribution level PMU becomes necessary. There have been a couple of efforts aimed at building such a device. However, in order to provide a solution to existing data quality issues, we had to build such a device from scratch.

Producing distribution level synchrophasors in compliance with existing standards is no easy task. Many things can go wrong between sampling the outlet voltage and reporting the respective synchrophasor. First, the sampling hardware must be very accurate to keep the error in voltage data as small as possible. We encountered data availability issues due to the GPS receiver missing the second pulse twice per hour, on average, thus not being able to accurately calculate the respective synchrophasors.

One of the most important aspects of calculating a standards compliant synchrophasor is having a strong software program. It would be best to use a common and well-documented programming language. It is the user defined program that has to deal with the need for precise synchronization between the time data is collected and GPS second pulses in order to provide the right timestamp. Such precise timing is required because even one voltage data point has a noticeable impact on producing an accurate synchrophasor; precise timing is also required to produce the much desired millidegree phase resolution. Nonetheless, networking expertise is needed to reliably present the calculated synchrophasor to a PDC server. Ideally, the production cost of such a distribution level PMU would not exceed $80 in order to keep it marketable.

More efforts have to be aimed at finding meaning for distribution level phase angles, as they are most difficult to accurately estimate and can give lots of insight into the power system behavior. So far, these phase angles do not have much meaning due to phase shifting transformers and other devices installed between different locations. Also, if comparing adjacent buildings, phase shift might be very small, only affected by the impedance across the locations in the feeder where each building is connected. In the transmission level, however, phase does have more meaning due to the long transmission lines with nothing along the way to interact with phase angles.

Nonetheless, distribution level synchrophasor research has come a long way during the last decade, and continues to grow in order to meet the increasing power grid monitoring demands.

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APPENDIX: MAIN PARTS OF PMU'S LABVIEW CODE

Figures 24 through 31 show the main parts of the LabVIEW code necessary to program a functioning PMU using NI's myRIO-1900 hardware.

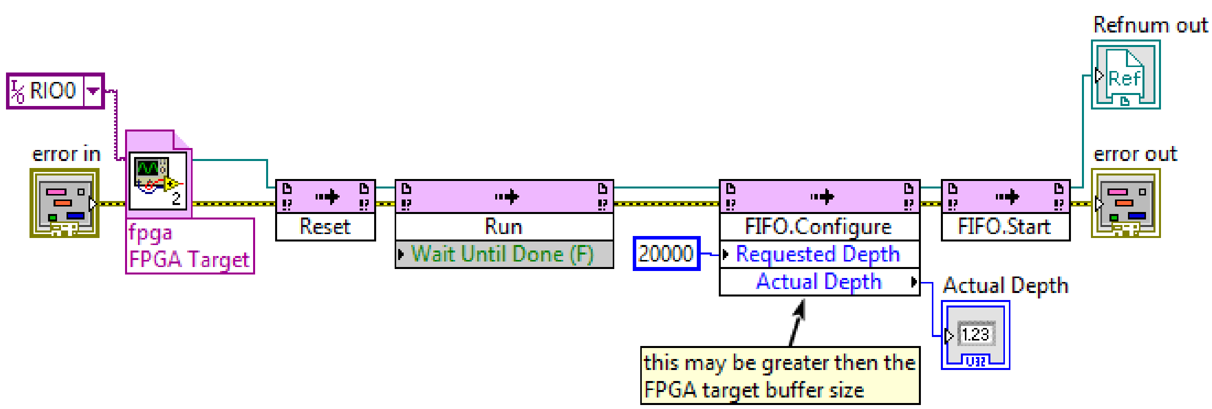

Figure 24: FPGA FIFO initialization

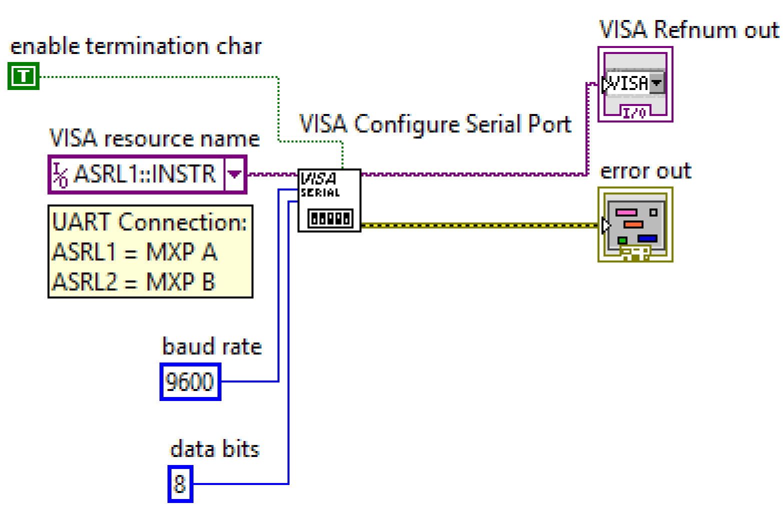

Figure 25: GPS initialization

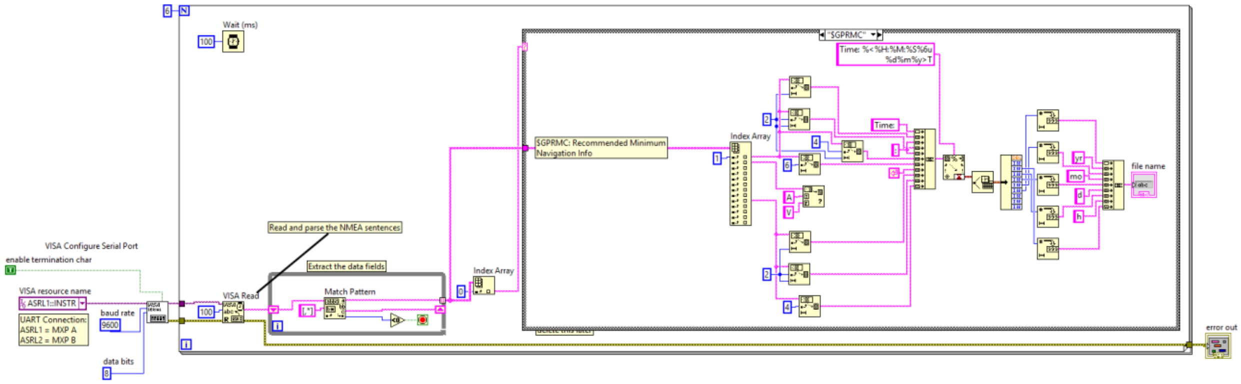

Figure 26: GPS reading algorithm

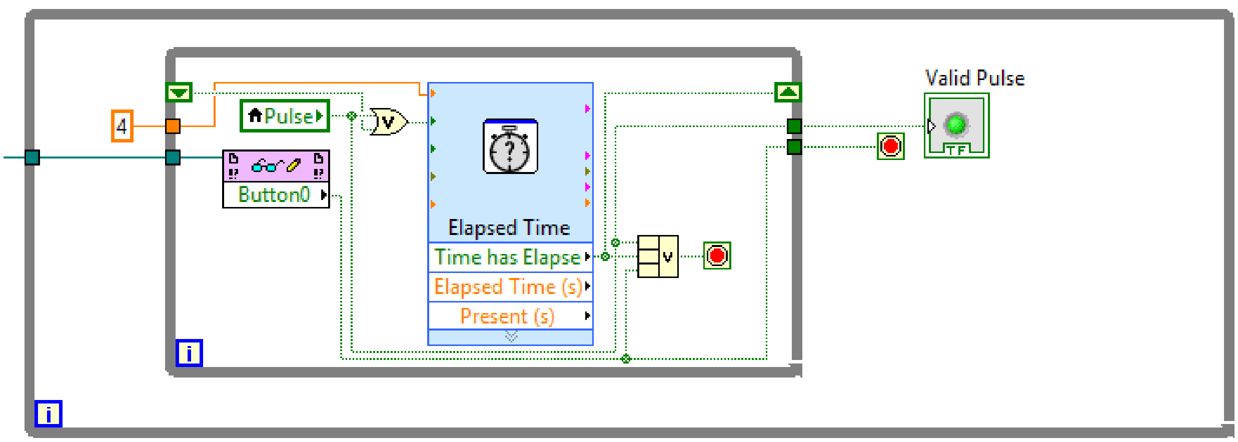

Figure 27: Valid pulse detection

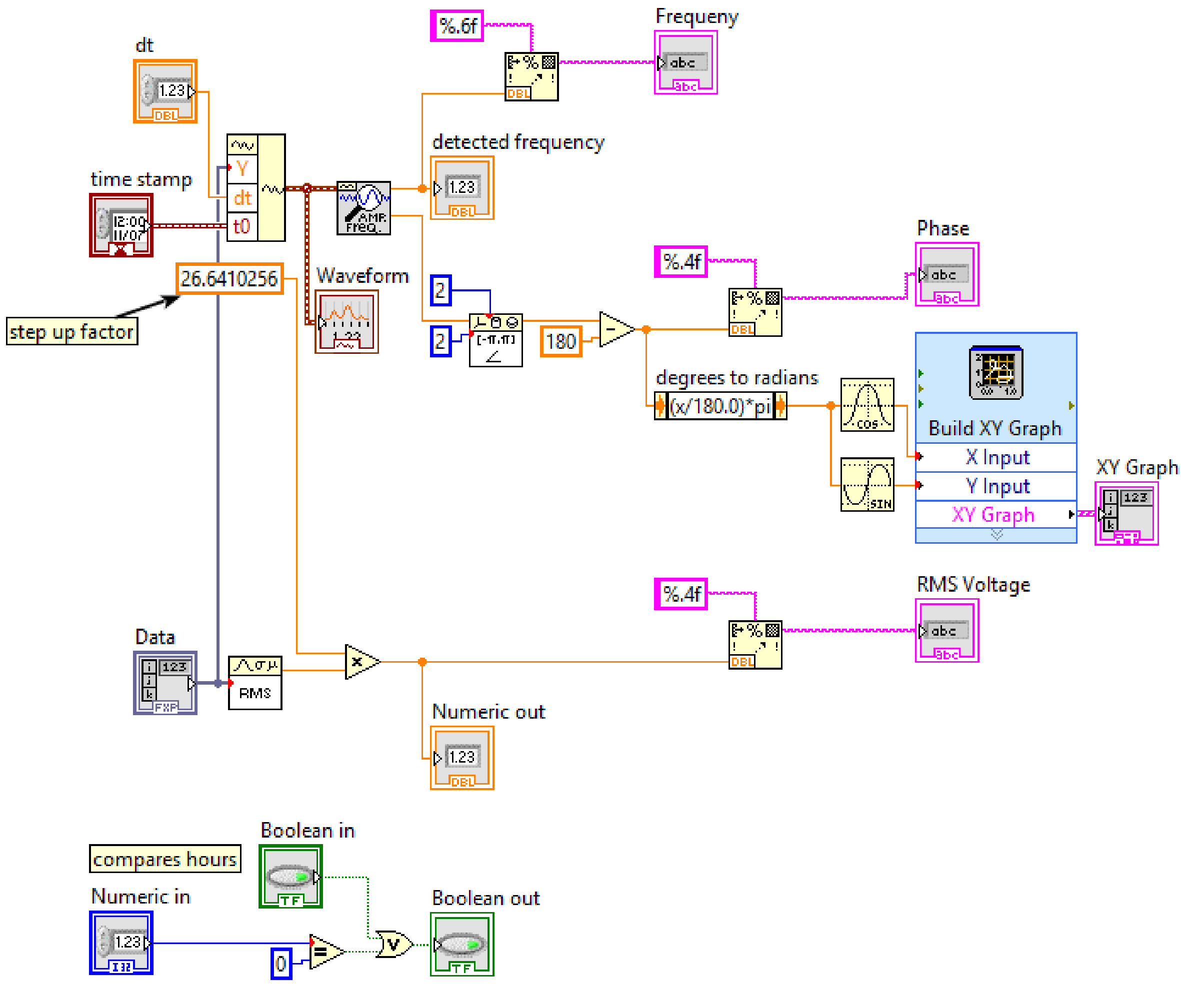

Figure 28: Voltage data manipulation for calculating frequency, phase, and RMS values

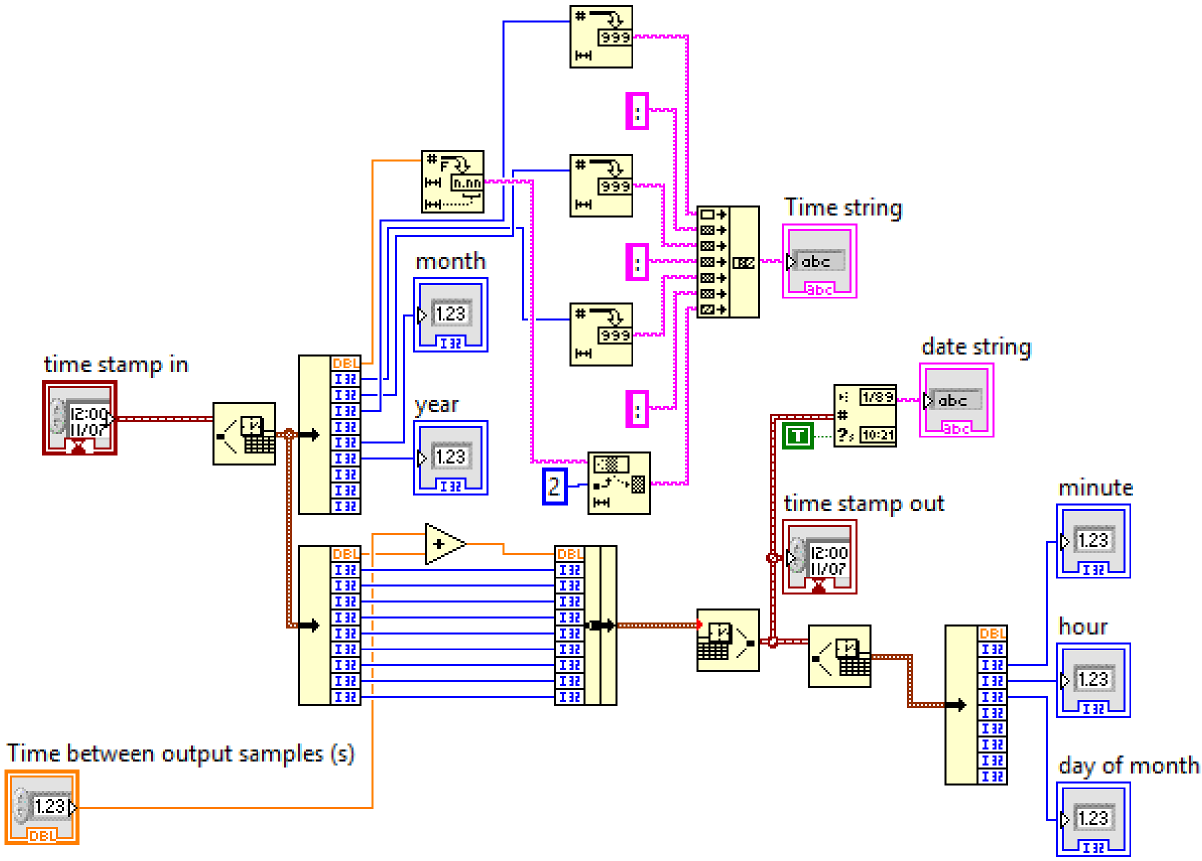

Figure 29: Time incrementation

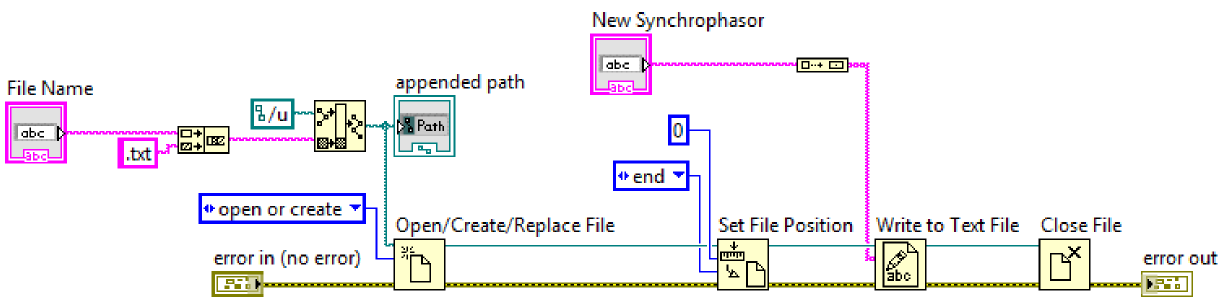

Figure 30: Saving data to file

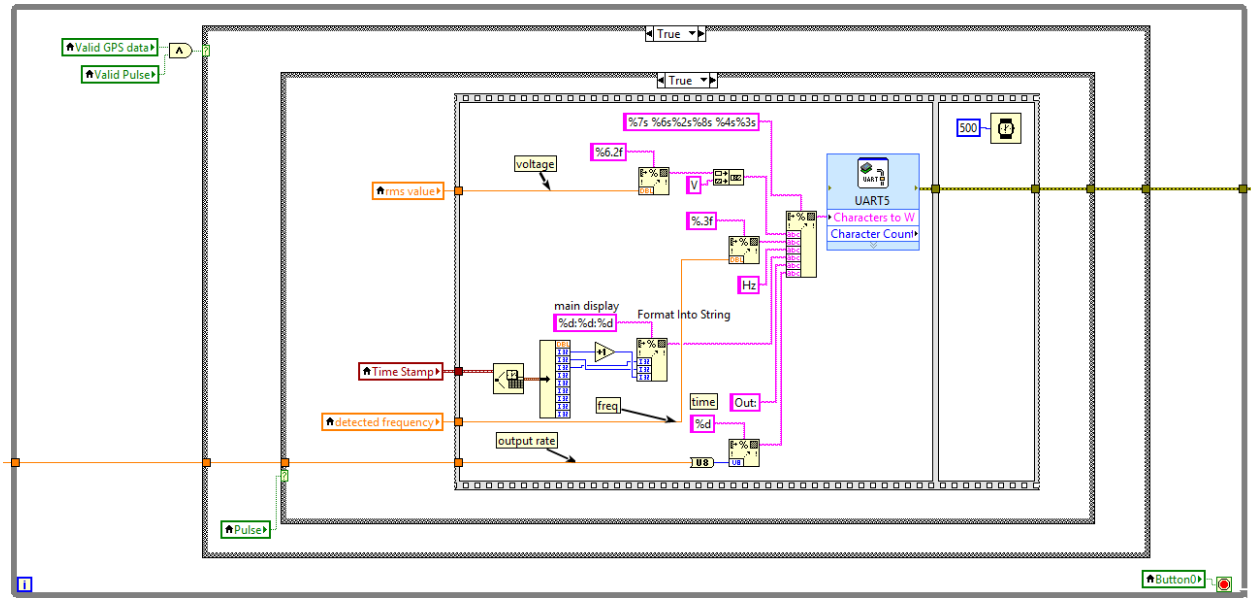

Figure 31: LCD output management